WATER REUSE TECHNOLOGY DEMONSTRATION PROJECT

Demonstration Facility Pilot Study
Treatment Trains For Reuse Applications
Final Report

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By

HDR Engineering, Inc.

BLACK & VEATCH

King County

Department of Natural Resources and Parks
Wastewater Treatment Division
Technology Assessment Program

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Acknowledgement

This project was conducted as a team effort involving many different people. Participants included King County staff, consultant team members (HDR / Black & Veatch), and vendor technicians and engineers.

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Executive Summary

Metropolitan King County is interested in introducing wastewater reclamation to its service area. To facilitate this initiative, a reuse demonstration project was conducted to evaluate and pilot test emerging technologies that could meet the County's goals for effluent water quality, operability, and cost.

The reuse applications ranged from basic tertiary treatments meeting Washington State Class A (Class A) reuse standards to stream augmentation and lake discharge, the latter requiring advanced wastewater treatment. The water quality goals to be met by a satellite treatment plant can vary considerably. Therefore, the baseline process must meet Class A water quality standards for oxidation, filtration and disinfection. Additional treatment could be required to meet more stringent levels of nutrient, metals, organics, and turbidity.

Following an in-depth screening of the individual treatment processes, two aerobic biological treatment trains were selected for testing in a nine-month pilot test. One uses a Biological Aerated Filter (BAF) and the other a Membrane Bioreactor (MBR) for wastewater oxidation. Other emerging technologies investigated for their small footprints and enhanced performance include Fuzzy Filter and ballasted flocculation (Actiflo and Densadeg) for primary treatment, Fuzzy Filter and microfiltration for tertiary effluent filtration, and reverse osmosis for advanced treatment.

Eleven BAF based treatment trains and four MBR based treatment trains were developed. Some of these trains included enhanced treatment by adding chemicals. Some treatment trains included unit processes that were not tested during the pilot study. A total of 19 different treatment trains are presented. These can meet the treatment objectives for all 12 reuse applications. In some cases, a given treatment option can meet more than one objective; in other cases enhanced treatment can expand the reuse opportunities.

The ultimate selection of a treatment train for a full-scale facility will depend on the objectives at the specific satellite site, the available space, and the current and future demand for reclaimed water.

Introduction

Metropolitan King County implemented a reuse demonstration project to evaluate, select, and pilot test technologies for high quality reuse water. To be included in this study, technologies had to have small footprints, low cost and the ability to be operated remotely. The project was geared towards two full-scale end uses. The primary end-use was for irrigation utilizing small (0.5 to 3 mgd) "satellite scalping plants." But because irrigation needs are seasonal, a combined sewer overflow (CSO) treatment could also be provided using part of the facility when water is not needed for irrigation. This would be for future potentially heavy uses, such as stream flow augmentation, or groundwater recharge. For this application, additions would be made to a satellite or major treatment plant to provide "advanced treatment."

The overall objective of the pilot testing program was to assess the ability of emerging wastewater treatment technologies to produce effluent quality meeting either Class A reclaimed water standards or more stringent water quality standards associated with other reuse opportunities being considered by King County.

Keeping in mind that the reason for this study was to gain enough knowledge to design an efficient reclamation plant in the near future, the specific goals for the pilot testing included the following:

- Evaluate new and emerging technologies and compare these with conventional treatment systems used for Class A reclaimed water production.
- Assess the feasibility of upgrading the "Baseline Class A Treatment Trains" to provide higher effluent quality through process modifications or additional treatment steps.
- Assess the capabilities of the process for seasonal operation.
- Assess the ability of the system to be operated unattended with minimum maintenance.
- Minimize the footprint of the facility.

The water quality goals to be met by a satellite treatment plant depend on the end-use purpose. Table 1 lists the expected water quality objectives that can be expected for various reclamation applications. The baseline process must meet Class A water quality standards. In addition to these considerations, disinfection will be required for all treatment trains.

Test Program

Overview

The pilot testing was conducted at the King County West Point WWTP inside of or adjacent to the Technology Assessment Test Facility. Facilities were designed and constructed to support testing a number of pilot units with several feed streams. Features of the pilot testing facilities included pumps, interconnecting piping, storage tanks, electrical, instrumentation and control, and SCADA.

A simplified pilot testing schematic is presented in Figure 1. The following technologies were tested:

- Primary treatment technologies:
  - Ballasted flocculation – Actiflo system
  - Ballasted flocculation – Densadeg system
  - Fuzzy Filter
- Biological (secondary) treatment technologies:

- Single-stage biological aerated filter
- Two-stage biological aerated filter
- Membrane bioreactor
- Tertiary treatment technologies:
  - Fuzzy Filter
  - Microfiltration
- Advance treatment using reverse osmosis

Table 1. Water Quality Classifications for Reclamation End-Uses

Water Quality	BOD mg/L	TSS mg/L	Total P mg/L	NH3-N mg/L	TN mg/L	Turb. NTU	TOC mg/L	TDS mg/L	Metals, Organics
Class A	30	30	- -	- -	- -	2	- -	- -	- -
Wetlands	20	20	1	Toxicity	3	2	- -	- -	Surface2
GW (percolation)	30	30	- -	- -	10	2	- -	- -	Site
GW (non-potable)	5	5	- -	- -	Site	2	- -	Site	Site
GW (potable)	5	5	- -	- -	10	0.1	1	Site	SDWA
Large Stream (marine)	30	30	3 – 5	2 – 3	- -	2	- -	- -	Surface1
Small Stream (marine)	10	10	1 – 2	1	- -	2	- -	- -	Surface1
Large Stream (lake)	30	30	0.1	2 – 3	- -	2	Pos	- -	Surface1
Small Stream (lake)	10	10	0.1	1	- -	2	Pos	- -	Surface1
Navigation Locks	30	30	Pos	1	Pos	2	- -	- -	Surface1
Lake Anticipated	10	10	0.01	1	- -	2	- -	500	SDWA
Lake Worst Case	10	10	0.01	0.02	0.6	2	2	100	SDWA/BG

Notes:
GW = Groundwater recharge
Pos = Possible limit
Site = Site specific criteria
Surface1 = Surface water standards with mixing zone
Surface2 = Surface water standards with no mixing zone
SDWA = Safe Drinking Water standards
BG = Background concentrations without mixing zone

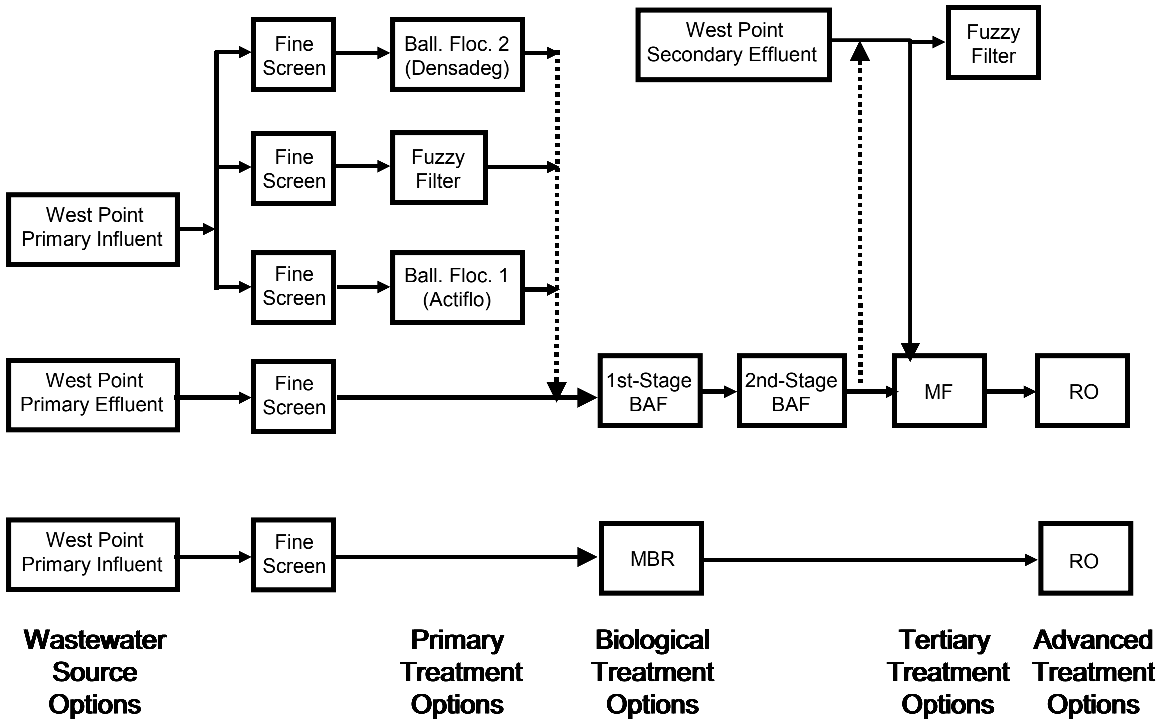

Figure 1. Pilot Testing Simplified Schematic.

The facilities were designed to test the BAF1 unit on the following feed streams: West Point WWTP primary effluent (WP PE), ballasted flocculation 1 (Actiflo) effluent, ballasted flocculation 2 (Densadeg) effluent, and Fuzzy Filter effluent. However, only the WP PE feed was supplied to BAF1. The limited time frame for testing the ballasted flocculation units under stable operating conditions precluded supplying effluent from these two units to BAF1. The Fuzzy Filter proved unsuitable for treating West Point Primary influent, so no Fuzzy Filter effluent was available to feed BAF1. Figure 1 indicates the potential feed to BAF1 from these units with a dashed line.

The facilities were also designed to allow BAF2 effluent to supply the Fuzzy Filter. However, the BAF2 flow rate was too low to support the Fuzzy Filter testing in a tertiary treatment application. Instead, West Point WWTP secondary effluent (WP SE) was supplied to this unit. Figure 1 indicates the potential feed from BAF2 to the Fuzzy Filter unit with a dashed line. Solid lines shown on Figure 1 depict actual flow patterns tested.

The same Fuzzy Filter unit was tested both as a primary and a tertiary treatment technology. It was first tested as a primary treatment unit where de-gritted raw wastewater (primary influent) was supplied to it. Then the feed piping was switched to supply it with WP SE for tertiary treatment testing. The same RO unit was used to treat both MBR effluent and MF effluent.

Operation

King County staff operated most of the pilot unit facilities. USFilter/Kruger provided its own operators for the Actiflo unit. The County used a contractor to facilitate the installation and removal of the pilot units. Each pilot unit vendor provided an onsite startup engineer to ensure that the unit was set up and operating as expected. The startup engineer coordinated with the County and contractor. Once startup was completed, County staff operated the units and collected data.

With the exception of the Actiflo unit, the pilot units were operated continuously, seven days per week. Each day, operators checked on the unit operation and recorded instrument readings associated with the operation of the unit. Some pilot units included PLCs and/or data loggers that logged key operating parameters. Each unit was linked into the SCADA system and the data was stored and archived by the County.

Sampling

Sampling and lab analyses were provided by King County. No outside testing was utilized, except for post-test membrane element cleaning for the RO unit. Except for the Actiflo and Densadeg units, the routine feed and effluent sampling for each pilot unit was performed using auto samplers configured to provide 24-hour composite samples. The USFilter/Kruger and Densadeg operators manually collected grab samples that were collected in a single vessel to provide a composite.

Special testing was also conducted to measure microbial, metals, and organic removals. County operators or laboratory staff collected grab samples of feed and effluent streams for special testing.

The West Point WWTP process laboratory analyzed general water quality parameters such as TSS, VSS, COD, BOD, total phosphorus, and TKN for primary influent, primary effluent and primary treatment unit effluents. The King County Environmental Laboratory analyzed the special parameters such as metals, microbial count, and other tests that required low detection limits.

Analytical methods are identified in Table 2.

Table 2 - Assignment for Analytical Measurements

Component	Method	WP Process Lab	KC Environ. Lab
CODt	Hach vials	y	
CODs	Hach vials	y	
BODt	Standard Methods	y	
BODs	Standard Methods	y	
TSS	Standard Methods	y	
VSS	Standard Methods	y	
TDS	Standard Methods	y	
TOC	Lab		y
Turbidity	Online/instrument	y	
TKN	Standard Methods	y	
NH4	Online, Hach vials	y	y
NO3	Online, Hach vials	y	y
TP	Standard Methods	y	y
Orthophosphate	Hach vials	y	y
Alkalinity	Standard Methods	y	
pH	Instrument	y	
Temperature	Online	y	
SDI	Operator on site	y	
EC	Instrument	y	

Coordination

The project team coordinated pilot testing. The project team included King County Technology Assessment Program engineers, plant operations and maintenance personnel, laboratory staff, the consultant team, and the pilot unit vendors. Each pilot unit was assigned a lead County operator and vendor pilot testing contact. Also, a member of the consultant team was assigned to one or more pilot units to develop the pilot unit detailed test plan, evaluate the data as it was collected and distributed by the County, schedule and coordinate conference calls between the County and vendor, and write the unit process report.

During the pilot testing, County operators prepared daily reports on the pilot performance. The County operators also prepared a weekly sampling plan, which was reviewed by the consultant pilot unit lead to make sure the sampling requirements were covered. Approximately every two weeks, the project team would have a conference call to discuss status of the testing and make mid-course corrections to the test plan as needed.

Description of Technologies and Their Performance

The pilot testing conducted at the West Point Wastewater Treatment Plant produced performance and design data for the various emerging reclamation technologies and provided experience with them as well. Performance goals were set specifically for this study. In many cases, the goals set for this study exceeded those needed to achieve Class A reclaimed water. This was done purposely to determine which units could produce water that meets Class A requirements and which could produce even cleaner water meeting the more ambitious performance goals. See individual unit process reports for specific performance and operational goals for the different processes. In this evaluation, the lower bar should be considered in assessing the potential for using the technology in a full-scale reclamation facility.

Following is an overview of the pilot results and experience with the various technologies. The pilot units were obtained from equipment suppliers as complete systems. The degree of control and redundancy was different for the various units. The most commonly encountered operational problem during the pilot testing was the ability to keep the units functioning due to equipment failure and the chain effect where the operation of one pilot unit impacts the operation of another unit. For example, feed pumping failure or lack of backwash storage water occurred a few times. See individual unit process reports for more details regarding the pilot operation. In most instances, the equipment deficiency is associated primarily with pilot testing and should not be a significant issue for full-scale plants, where redundant equipment and facilities are provided for critical components.

This description focuses on the performance of the technology under the conditions tested at West Point and how these technologies could be used in a full-scale reclamation facility. The water quality shown in the tables represents effluent from the particular pilot unit. A footprint size is listed for each technology. The footprint is calculated based on the design criteria and includes the unit process plus an allowance for ancillary systems (blower, chemical feed, controls).

Ballasted Flocculation – Actiflo

Actiflo is a high performance, compact clarification process using micro-sand enhanced flocculation and settling. A coagulant, a polymer, and microsand are added to the wastewater to form large, heavy particles that settle rapidly to the bottom of a settling tank. Clarification efficiency is further increased by the use of the lamella tubes in the settling tank. The use of chemical coagulants makes the process more flexible, more complex and more costly to operate.

Table 3 shows the results from the pilot demonstration facility.

Table 3. Actiflo in Reuse Treatment Plant for Primary Treatment.

Issue	Pilot Experience
Performance	TSS removal > 90%
	COD removal > 60%
Enhanced treatment	TP removal > 90%
	Copper and zinc removed
Startup	Process start up in minutes to reach stable performance
Unattended operation	Process automated. Routine monitoring required.
Hydraulic loading	60 gpm/sf
Footprint	100-200 sf/mgd

The Actiflo process is an attractive option for primary treatment, with a high removal efficiency for COD and TSS. It can be used for phosphorus removal when chemicals are added. The process starts up rapidly and has a compact footprint. The main concern with Actiflo is its ability to recover sand from the settled solids flow under continuous, long-term operation. While sand loss and mudball formation were not problems in the pilot study, long-term operational experience is required to quantify these issues.

Ballasted Flocculation – Densadeg

Densadeg is a high performance, compact ballasted-flocculation process. A coagulant and a polymer are added to a sludge recycle stream and blended with the influent to form large, heavy particles that settle rapidly to the bottom of a settling tank. Clarification efficiency is further increased by the use of the lamella tubes in the settling tank. The use of chemical coagulants makes the process more flexible, more complex and more costly to operate. Maintaining a stable sludge blanket is a critical component of this treatment process.

Table 4 shows the results from the pilot demonstration facility.

Table 4. Densadeg in Reuse Treatment Plant for Primary Treatment.

Issue	Pilot Experience
Performance	TSS removal > 85%
	COD removal > 60%
Enhanced treatment	TP removal > 85%
Startup	Process start up in about 35 minutes to reach stable performance
Unattended operation	Process automated. Routine monitoring required. Maintaining a stable sludge blanket is key to proper operation.
Hydraulic loading	40 gpm/sf
Footprint	150-250 sf/mgd

The Densadeg process is an attractive option for primary treatment, with a high removal efficiency for COD and TSS. It provides the ability for phosphorus removal by adding chemicals. The process starts up rapidly and has a compact footprint.

Fuzzy Filter for Primary Treatment

The Fuzzy Filter is a high-rate filtration process using uniquely designed media that is highly porous and compressible. The porosity of the media can be changed by compressing the media during operation to accommodate changing influent conditions. Filtration rates are much higher than for conventional filters.

The Fuzzy Filter does not appear to be suitable for use in a primary treatment application for King County. Breakthrough of solids was observed within a short period of time (i.e., less than one hour) due to the high solids loading and blinding of the first layer of filter media which led to short circuiting along the walls of the pilot unit. The footprint for primary treatment by the Fuzzy Filter was not determined.

Biological Aerated Filter for BOD removal (BAF1)

The biological aerated filter (BAF) is a high-rate, fixed-film biological secondary treatment process that oxidizes BOD and ammonia in wastewater. Primary effluent flows upward through a media bed (expanded sand media in BIOFOR), with aeration supplied to create an aerobic environment. The biomass attached to the filter media removes soluble pollutants biologically and removes insoluble pollutants by filtration, eliminating the need for a separate solids separation stage for effluent clarification. Multiple cells are used to allow some of the units to be taken offline for backwash. Under typical operating conditions cells are brought online to match the flow to the facility. The BAF is backwashed to remove excess biomass and clean the bed. The backwash frequency is adjusted to achieve optimal performance. Storage for this backwash water (treated effluent) is required. In a satellite plant, spent backwash water can be sent to sewer; it may require storage if treated on site. Fine screening and primary clarification are required to protect the media and nozzles from plugging.

Table 5 shows the results from the pilot demonstration facility.

Table 5. BAF in Reuse Treatment Plant for BOD Removal.

Issue	Pilot Experience
Performance	TSS effluent ~ 25-40 mg/L
	BOD effluent ~ 25-40 mg/L
Enhanced treatment	See nitrification BAF
Startup	Process start up in about 2 weeks
Unattended operation	Process automated and ran unattended. Backwash settings are key to good performance.
Organic loading	275 lb BOD/1000 ft^3/d
Footprint	600-1,000 sf/mgd

The BAF is a compact process that provides oxidation of wastewater. The BAF clearly showed that it "oxidized" wastewater, and would satisfy the oxidation step in Class A reclaimed water criteria. However, the effluent quality from a single-stage BAF did not meet the typical secondary standards under the conditions tested. Therefore, the process must be followed by a second stage BAF (see nitrifying BAF discussion) or a low-loaded sand filter to remove TSS and BOD.

Biological Aerated Filter for Nitrification (BAF2)

The biological aerated filter (BAF) for nitrification is a high-rate, fixed-film biological treatment process that is designed to oxidize ammonia to nitrate. Secondary effluent flows upward through a media bed (expanded sand media in BIOFOR), with aeration supplied to create an aerobic environment. The nitrifying biomass grows on the filter media and oxidizes ammonia. Biomass is retained on the media and wasted with an occasional backwash, eliminating the need for a separate solids separation stage for effluent clarification. Multiple cells are used to allow some of the units to be taken offline for backwash. Under typical operating conditions cells are brought online to match the flow into the facility. The BAF is backwashed to remove excess biomass and clean the bed. The backwash frequency is adjusted to achieve optimal performance. Storage for the backwash water (treated effluent) is required. In a satellite plant, spent backwash water can be sent to sewer; it may require storage if treated on site. Fine screening is required to protect the media and nozzles from plugging.

Table 6 shows the results from the pilot demonstration facility.

Table 6. BAF in Reuse Treatment Plant for Nitrification.

Issue	Pilot Experience
Performance	TSS effluent <15 mg/L
	BOD effluent <10 mg/L
	NH4 effluent < 2 mg/L
Enhanced treatment	NH4 effluent < 1 mg/L at reduced loading
Startup	Process start up in less than 4 weeks
Unattended operation	Process automated and run unattended. Backwash settings are key to good performance.
Hydraulic loading	4.5 gpm/sf
Footprint	400-800 sf/mgd

The nitrification BAF is an attractive option for providing nitrification of secondary effluent. The loading to the system can be manipulated to provide the desired degree of treatment. In addition, using a two-stage BAF process to provide stable operation for BOD and TSS removal is attractive, but will be more costly.

Membrane Bioreactor (MBR)

The MBR is a suspended-growth secondary treatment process. Screened raw wastewater is fed to a single activated sludge tank (or to a series of activated sludge basins if nutrient removal is required) and then to a membrane tank. Effluent is drawn through hollow-fiber submerged membranes in the membrane tank. No primary or secondary clarifier is used. A vacuum pump draws suction on the fibers to draw effluent through the membranes. Several different types of membranes have been used in this process. The Zenon pilot unit tested uses a modified polymer with 0.1 μm absolute pore size hollow fiber membrane.

The process provides a firm barrier to remove solids and other particulate pollutants. The pore size is small enough to exclude bacteria, and even some virus removal is possible. Phosphorus can be removed biologically (as attempted in the pilot study) or chemically. Biological phosphorus removal was not established during the pilot study.

Table 7 shows the results from the pilot demonstration facility.

Table 7. MBR in Reuse Treatment Plant for Secondary or Advanced Treatment.

Issue	Pilot Experience
Performance	Turbidity < 0.06 NTU at 90% percentile (< 0.015 NTU average)
	TSS effluent below detection
	BOD effluent < 2 mg/L
Enhanced treatment	NH4 effluent < 2 mg/L
	TN <10 mg/L (expected with BNR design, not demonstrated)
	TP < 1 mg/L[1]
	TP < 0.1 mg/L (expected with chemical addition)
	Coliform between below detection to 1.7 x 10^3 CFU/100 mL
Startup	Process start up in less than 14 days (backpulse mode)
Unattended operation	Process automated and run unattended.
Design flux	13 gfd
Aerobic sludge age	8 d
Footprint	2,500 to 3,500 sf/mgd

Note:
1. Influent TP between 2 and 5 mg/L. Enhanced biological phosphorus removal attempted but not clearly demonstrated.

The MBR is an attractive process for reclamation application. It is compact, and it consolidates primary clarification, secondary treatment, nutrient removal, and filtration into one process. Effluent from the MBR can be sent directly to RO for demineralization. The performance and reliability of the process is very good. The main concern is that impacts of a long-term operation on membrane flux and durability are unknown. Even though membrane cost has declined over the past few years, membrane replacement is still the key cost component for this process. Effective cleaning of the membrane is critical to maintaining the flux.

Fuzzy Filter for Tertiary Treatment

The Fuzzy Filter is a high-rate filtration process using uniquely designed media that is highly porous and compressible. The media can be compressed during operation to accommodate changing influent conditions. Filtration rates are much higher than for conventional filters. The same Fuzzy Filter pilot unit was used to test both primary and tertiary treatments by switching the influent feed from primary influent to secondary effluent.

Table 8 shows the results from the pilot demonstration facility.

Table 8. Fuzzy Filter in Reuse Treatment Plant for Secondary or Advanced Treatment.

Issue	Pilot Experience
Performance	Turbidity effluent < 2 NTU (90th percentile) if influent < 10 NTU
	TSS effluent < 5 mg/L
	Total BOD effluent < 2 mg/L
Enhanced treatment	NH4 effluent < 2 mg/L
	TP effluent < 0.5 mg/L (low influent levels, require high chemical dose)
Startup	Process start up immediately
Unattended operation	Process automated and run unattended.
Hydraulic loading	30 gpm/sf
Footprint	500 to 900 sf/mgd

The Fuzzy Filter performance was very much influenced by the feed water quality. Spikes in influent turbidity are not readily captured in the Fuzzy Filter. High solids loadings will also reduce the filter performance and the filter run time. With a stable influent feed water quality, the Fuzzy Filter performed well. Chemical feed improved the performance of this process and its stability.

Microfiltration

Microfiltration (MF) is one of the membrane filtration technologies commonly used in water and wastewater treatment. The general concept of the process is to physically separate the contaminant from the water by passing the flow through a membrane. The membranes are made of plastic or polymeric material that contains millions of small pores. The pores are large enough to allow water to pass through, yet small enough to restrict the passage of undesirable materials such as particulate matter and pathogenic organisms. The driving force for low-pressure membrane filtration can be either pressure or vacuum.

The Pall microfiltration membrane evaluated in this pilot study has a pore size of 0.1 μm and operates at low pressures of approximately 5-30 psi. MF has proven to be an effective secondary wastewater effluent filter to meet effluent turbidity limits for reuse applications and pretreatment for Reverse Osmosis (RO). Water is driven from the outside to the inside of the fibers and this filtrate is collected in the filtrate line, which is still under pressure from the feed pump. This line can discharge the filtrate to an end use or supply a downstream unit.

Table 9 shows the results from the pilot demonstration facility.

Table 9. MF in Reuse Treatment Plant for Advanced Treatment.

Issue	Pilot Experience
Performance	Turbidity effluent < 0.06 NTU (95th percentile)
	TOC effluent < 13 mg/L (particulate removal only)
Enhanced treatment	TP effluent < 0.1 mg/L (low influent levels, require high chemical dose)
Startup	Process start up without lag time
Unattended operation	Process automated and ran unattended.
Flux	30 gfd
Footprint	1,500 – 3,000 sf/mgd

The MF effectively removes particles and pollutants associated with particles. Soluble components are not removed. The operation is affected by the feed water quality. Spikes in influent turbidity lead to a rapid pressure buildup and require more frequent cleaning. Modest influent turbidity fluctuations can be attenuated with increased backwash, but for long-term operation, the flux and backwash frequencies must be selected to provide the desired water recovery.

Reverse Osmosis

Reverse osmosis (RO) has been used for advanced wastewater treatment and water reclamation for many years to produce exceptionally high quality water. RO uses a semi-permeable membrane that allows water to pass through the membrane under pressure at a much greater rate than dissolved material. Pressure is applied across the membrane to overcome the osmotic pressure and force water through the membrane. Water and a small amount of the dissolved material diffuse through the semi-permeable membrane. The purified RO water is called "permeate" or "product."

The membrane type and material determines the solute transport characteristics of the RO system. A thin-film composite polyamide membrane was tested in the RO pilot study. This membrane is not chlorine tolerant but has excellent salt rejection and pressure ratings. The unit operated at transmembrane pressures ranging from 100 to 300 psi and fluxes of 8 to 14 gfd (temperature corrected to 20 ^{o}C).

Table 10 shows the results from the pilot demonstration facility.

Table 10. RO in Reuse Treatment Plant for Advanced Treatment.

Issue	Pilot Experience
Performance	TDS < 110 mg/L (>92% removal)
	TOC effluent < 1.6 mg/L (83% removal)
	NH4-N < 0.02 mg/L (>90% removal)*
	NO3-N < 0.2 mg/L (>97.5% removal)*
	TP < 0.02 mg/L (>99% removal)*
	Metals present reduced to below detection
Enhanced treatment	This is an advanced treatment system
Startup	Process started up immediately
Unattended operation	Process automated and ran unattended.
Flux	9 gfd
Footprint	2,000 – 5,000 sf/mgd

Note
* Permeate often at or below detection limit.

RO effectively removes soluble and particulate pollutants. Feed to the RO system must be essentially particle free to avoid membrane fouling. Large molecules are effectively removed in the process. Therefore, RO can be used to meet stringent criteria. Table 11 shows the required feed water quality to meet certain effluent nutrient objectives with RO.

Table 11. Maximum Possible Feed Concentration to Meet Effluent Targets with RO Treatment.

Compound	Removal %	Effluent target mg/L	RO feed max mg/L
Ammonia-N	90%	2	20
Ammonia-N	90%	1	10
Ammonia-N	90%	0.02	0.20
Nitrate-N	97.5%	10	400
Nitrate-N	97.5%	3	120
Nitrate-N	97.5%	0.6	24
Phosphate-P	99%	1	100
Phosphate-P	99%	0.1	10
Phosphate-P	99%	0.01	1.0

Pilot Performance Summary

Table 12 summarizes the results from the pilot study in terms of the ability of the unit processes to meet the pilot objectives. Each unit process is rated in terms of its success in meeting the pilot objectives. The following symbols are used in Table 12:

- ✓ indicates meeting most performance goals.

- ✓✓ indicates exceeding all performance goals.
- x indicates not meeting objective.
- - indicates that the feature cannot be evaluated due to lack of information or inability to modify process.

The following features are rated:

- Performance – rated in terms of the target performance goals of pilot study.
- Enhanced treatment indicates the ability to meet enhanced performance goals using chemical addition. Not all processes have enhanced goals.
- Rapid startup reflects the ability to use the process in seasonal mode, i.e. its ability to be started up quickly (within a couple of weeks).
- Unattended operation reflects the ability to operate remotely with SCADA control. The rating is projected based on the attention requirements from pilot experience.
- Footprint is rated in terms of a relative comparison with conventional treatment.

Table 12. Summary of Unit Process Features During Pilot Study.

	Application	Performance	Enhanced Treatment	Rapid Startup	Unattended	Footprint
Actiflo	Primary	✓✓	✓✓	✓✓	✓	✓✓
Densadeg	Primary	✓✓	✓✓	✓	✓	✓✓
Fuzzy Filter	Primary	x	x	✓	x	-
BAF1	BOD rem	✓[1]	-	✓✓	✓	✓✓
BAF2	BOD rem	✓✓	-	✓	✓	✓✓
BAF2	Nitrification	✓	-	✓	✓	✓✓
MBR	Nitrification	✓✓	-	✓✓	✓✓	✓✓
MBR	BNR	✓✓	-	✓✓	✓✓	✓✓
Fuzzy Filter	Secondary	✓	✓	✓✓	✓	✓✓
MF	Tertiary	✓✓	✓✓	✓✓	✓	-??-
RO	Tertiary	✓✓	✓✓	✓✓	✓✓	-

Notes
1. Did not meet BOD objectives but provided well oxidized effluent

Table 12 shows that the pilot units in general were able to meet process objectives. The Fuzzy Filter tested in a new application for primary treatment was not successful. The BAF performed well, but effluent from the single stage was not able to meet objectives consistently (20 mg/L BOD and TSS at 90th percentile) but met the objectives at the 50th percentile. The MBR performed well as long as membrane fouling was avoided. Performance of most processes could be enhanced with chemical treatment for phosphorus removal.

Performance of a full-scale process is expected to exceed that the performance levels measured in the pilot study. Short-circuiting (which was experience in this pilot study) is limited in full-scale systems, and backup and redundant units are included in the design of full-scale facilities to prevent other problems associated with pilot units (lack of backwash water, instability of one process unit affecting another process operation, etc.).

Process Enhancements not Pilot Tested

Class A water does not require a nutrient removal. However, for other purposes such as stream recharge, the treatment process must include nitrogen removal through denitrification and phosphorus removal to concentrations below 0.5 mg/L. In order to achieve these limits, additional treatment using unit processes not tested in this pilot study can be used. Three additional unit processes are included in some treatment trains: ballasted flocculation for secondary phosphorus removal, conventional filtration, and a submerged biological filter for denitrification.

Ballasted Flocculation for Secondary Phosphorus Removal

To achieve phosphorus limits below 0.2 mg/L, significant chemical doses (20-50 mg/L) of coagulant are required in order to provide reliable phosphorus removal in a filtration step. At these high doses, filters tend to blind relatively quickly, and an additional solids-removal step is required ahead of filtration. Ballasted flocculation can be used in lieu of tertiary clarifiers to remove chemical solids associated with phosphorus removal.

Even though a ballasted-flocculation process was not piloted during the demonstration project for secondary treatment, testing of ballasted flocculation for primary treatment did provide experience with the equipment. Ballasted flocculation has been used full-scale for tertiary treatment and is an attractive alternative to conventional tertiary clarification.

Conventional Filtration

The term conventional filtration is used to refer to established filtration technologies known to produce Class A effluent quality. Conventional filtration could include filtration using a dual media, a triple media, a mixed media, Dynasand, or other approved filters. Of special interest, are those filters that can tolerate high solids loading (dual media, deep bed coarse media, etc.) since that allows enhanced chemical addition for phosphorus removal.

Submerged Biological Filter for Denitrification (SBF)

The submerged biological filter (SBF) process takes the BAF technology to the next step for denitrification. A submerged unaerated biological active filter is used with methanol added to the feed to provide a carbon source for denitrification. Tertiary fixed-film denitrification has been used in full scale facilities using coarse media filters, SBF, and fluidized beds. All these processes require a carbon source to stimulate denitrification.

Treatment Trains

Treatment trains evaluated in this study included processes required for reclamation criteria, which are oxidation, filtration and disinfection. There are two groups of treatment trains based on the oxidation processes: the BAF trains and MBR trains.

Based on our pilot results and on full-scale experiences elsewhere, the treatment trains are arranged in a number of potential sequences that seemed to have the potential to operate well. These trains were then evaluated in terms of the reuse applications where they could be implemented to meet the anticipated effluent criteria for that application.

Enhanced treatment is possible for some treatment trains. Enhanced treatment refers to the ability to improve the performance of the train to meet higher standards with minor changes. The most common change is adding a chemical to precipitate phosphorus. These modifications are designated with the letter "E" attached to the treatment train name in the sections that follow.

Some conventional treatment technologies can perform as well as the technologies evaluated in this study, (e.g., conventional primary clarifiers could be used instead of ballasted flocculation to provide primary treatment). However, if a conventional treatment is used in a treatment train, the other treatment units in that train must be sized accordingly to accommodate the performance expected by the conventional process (e.g., conventional primary clarifiers will remove about 35% BOD, compared to 60% expected using ballasted flocculation).

Table 13 shows a summary of the expected effluent quality from the various unit process tested during the pilot study and others included in the treatment trains. The effluent quality should be representative of a typical municipal wastewater. Some parameters are indicated as DL (below detection limit). A dash "-" indicates that the unit process will not remove that particular compound.

Table 13. Effluent Quality From Various Treatment Units

Process	BOD mg/L	TSS mg/L	Turbidity NTU	NH4 mg/L	TN mg/L	TP mg/L
Ballasted Flocculation	80-100	15-30	-	-	-	0.5-1.0
BAF1	25-40	25-40	-	-	-	-
BAF2	10	15	-	1	-	-
SBF*	-	-	-	-	10*	-
MBR	DL	DL	0.06	0.015	10*	0.1*
FF	2	5	2	-	-	0.5
Conv Filter*	2*	2*	1*	-	-	0.3
MF	DL	DL	0.06	-	-	0.1
RO	DL	DL	-	-90%	-97.5%	-99%

Note:
* Expected performance – not demonstrated in pilot unit
DL = Below detection limit

Expected performance for a typical municipal wastewater

BAF Based Treatment

There were eleven BAF treatment trains, and they are named B1 through B11. All BAF treatment trains use ballasted flocculation as a primary treatment. The main differences in the treatment trains revolve around the filtration step and the need for ammonia oxidation and enhanced treatment.

Train B1. Headworks – Ballasted Flocculation – BAF1 – Conventional Filter – Disinfect

Train B1 uses conventional filtration to satisfy the filtration requirement. Because the BAF effluent is relatively high in effluent TSS, the filter must be designed for high solids loading.

Adding chemicals to the filtration step for phosphorus removal can enhance the process train performance. However, due to the high solids loading, only a modest additional phosphorus removal (to approximately 0.3 mg/L) could be expected with additional chemical feed. Adding a secondary ballasted flocculation or clarifier could improve performance. However, note that the reuse applications that require enhanced phosphorus removal also require nitrification and/or nitrogen removal. Therefore, enhanced treatment of Train B1 provides little additional benefit in terms of reuse potential.

Train B2. Headworks – Ballasted Flocculation – BAF1 – MF – Disinfect

Train B2 uses microfiltration to satisfy the filtration requirement. The MF must be designed to handle high TSS and maintain acceptable run times.

Adding chemicals to the MF feed for phosphorus removal can enhance the process train performance. However, reuse applications that require enhanced phosphorus removal also require nitrification and/or nitrogen removal. Therefore, enhanced treatment of Train B2 provides little additional benefit in terms of reuse potential.

Train B3. Headworks – Ballasted Flocculation – BAF1-BAF2 – Fuzzy Filter – Disinfect

This treatment train uses a two-stage BAF to provide nitrification. The Fuzzy Filter is used for the filtration step. Pilot experience showed that this treatment mode stabilizes the treatment process due to the more consistent effluent from the second BAF. This treatment train will be more reliable than a single-stage BAF and will provide nitrified effluent.

Train B3E. This treatment train is a Train B3 with added chemicals to achieve phosphorus removal. Coupling phosphorus removal with nitrification allows the treatment train to be used for large stream (marine) applications. This train could meet small-stream (marine) requirements if the influent phosphorus concentration is low (below 4 mg/L).

Train B4. Headworks – Ballasted Flocculation – BAF1-BAF2 – Ballasted Flocculation – Fuzzy Filter – Disinfect

This treatment train is similar to Train B3, but adds secondary ballasted flocculation for improved phosphorus removal, and it meets reuse criteria for large- and small-stream (lake) discharge. This train provides nitrification. Pilot experience showed that this treatment mode stabilizes the treatment process due to the more consistent effluent from the second BAF. This treatment train will be more reliable than a single-stage BAF, and it will provide nitrified effluent. This is an enhanced train, with chemical addition to achieve low phosphorus limits.

Train B5. Headworks – Ballasted Flocculation – BAF1-BAF2 – MF – Disinfect

This treatment train, similar to Trains B3 and B4, provides nitrification with second-stage BAF. Pilot experience showed that this treatment mode stabilizes the treatment process due to both the more consistent effluent from the second BAF and the more reliable effluent produced by the MF barrier. Using MF in the filtration step, this train can produce a high quality effluent that can be sent to RO if needed.

Train B5E. This treatment train is a Train B5 with added chemicals to achieve phosphorus removal. Coupling chemical addition with MF allows this train to produce an effluent with very low (< 0.2 mg/L) phosphorus. Adding chemicals to achieve phosphorus removal is a definite benefit, since nitrification is achieved, and this would produce water that could be used for more reuse opportunities. Very low effluent phosphorus can be achieved with chemical addition and MF.

Train B6. Headworks – Ballasted Flocculation – BAF1-BAF2-SBF – Fuzzy Filter – Disinfect

This treatment train is similar to Train B3, but adds denitrification for nitrogen removal. This opens the door for reclaiming water for wetlands and some groundwater recharge options. Groundwater recharge may require a TDS limit that could require RO. RO cannot be added directly to this train due to the relatively high effluent turbidity from the Fuzzy Filter. Since the actual limits are not known, this treatment train remains an option only for applications without a TDS limit.

Train B7. Headworks – Ballasted Flocculation – BAF1-BAF2-SBF – Ballasted Flocculation – Fuzzy Filter – Disinfect

This treatment train is similar to Train B4, but adds denitrification for nitrogen removal. This opens the door for reclaiming water for wetlands and some groundwater recharge options. Groundwater recharge may require a TDS limit that could require RO. RO cannot be added directly to this train due to the relatively high effluent turbidity from the Fuzzy Filter. Since the actual limits are not known, this treatment train remains an option only for applications without a TDS limit.

Train B8. Headworks – Ballasted Flocculation – BAF1-BAF2-SBF – MF – Disinfect

This treatment train is similar to Train B5, but adds denitrification for nitrogen removal. This opens the door for reclaiming water for wetlands and some groundwater recharge options. Groundwater recharge may require a TDS limit that could require RO. With MF in the train, RO can be added at the end, and therefore this treatment train remains an option.

Train B9. Headworks – Ballasted Flocculation – BAF – MF – RO – Disinfect

Adding RO to the treatment train provides the ultimate barrier for TDS and TOC removal. The RO will also remove molecules, ions and all particles. Since nitrogen and phosphate are removed very well with RO, this process train can be used to meet stringent effluent limits (see Table 11).

Train B10. Headworks – Ballasted Flocculation – BAF1-BAF2 – MF – RO – Disinfect

Train B10 adds nitrification to Train B9. The conversion of ammonia to nitrate also increases the total nitrogen removal since RO is more effective at removing nitrate than ammonia.

Train B11. Headworks – Ballasted Flocculation – BAF1-BAF2-SBF – MF – RO – Disinfect

Train B11 adds denitrification to Train B10. This allows the treatment train to meet the most restrictive water quality standards. Chemical enhancement may be required to reduce phosphate to very low limits. This train is able to meet the worst-case lake requirements with one possible exception: the effluent ammonia from BAF2 is high, and we assumed no additional ammonia removal before RO; therefore in order to meet the 0.02 mg/L NH4-N value, the feed to the RO must be below 0.2 mg/L, which is lower than the BAF2 concentrations measured during the pilot study.

MBR Based Treatment

Train M1. Headworks – MBR – Disinfection

Train M1 is the simplest MBR train, designed to meet basic Class A standards. The effluent quality from the membrane exceeds the typical Class A requirements. Because the sludge age for the MBR is high (over 8 days at least, and likely 15-20 days) the system nitrifies. This train is designed without denitrification.

Train M2. Headworks – MBR (BNR) – Disinfection

Train M2 is similar to Train M1 but includes denitrification and phosphorus removal. The phosphorus removal can be biological or chemical.

Train M3. Headworks – MBR – RO – Disinfection

Train M3 includes RO for advanced treatment. This treatment train can meet the most restrictive phosphorus limits expected with enhanced chemical addition. Train M3 can also meet the most restrictive nitrate standard, even without denitrification in the MBR. However, the MBR effluent nitrate must be less than 24 mg/L to achieve the 0.6 mg/L final effluent TN after RO, and that was feasible under the test conditions. However, if the influent nitrogen is higher than under our pilot testing conditions (testing condition influent ammonia was 5 to 25 mg/L), this option may not be able to meet the most restrictive discharge criteria.

Train M4. Headworks – MBR (BNR) – RO – Disinfection

This train enhances Train M3 by adding denitrification to consistently meet the most restrictive effluent nutrient criteria.

Summary and Conclusions

Table 14 lists component processes, effluent characteristics, and potential reuse applications for each treatment train. The symbol "E" designates a process enhancement that uses chemical addition.

- Nine potential reuse applications are presented. Each on has its own unique water quality goal, ranging from a basic Class A requirement for oxidation-filtration-disinfection to enhanced treatments for nutrient, metals, organics, or turbidity removals.
- Eleven BAF-based treatment trains and four MBR-based treatment trains are able to meet Class A and advanced treatment requirements. Adding chemicals can enhance the performance of some of these treatment trains. Many treatment trains are able to meet multiple objectives, and some can be modified to achieve higher effluent standards.
- Suitability of the various trains is determined by the requirements of the application for which it is intended:
    - Some reuse applications do not require nutrient removal, e.g., if only basic Class A water is needed.
    - Some applications require total nitrogen removal, but not specifically ammonia or phosphorus removal.
    - Some reuse applications require nutrient removal.
    - Some reuse applications require advanced treatment. These requirements vary, with some requiring removal of phosphorus, others requiring total nitrogen removal, and yet others requiring removal of turbidity, metals, or organics.
    - Some reuse applications require TDS removal. These reuse applications force the treatment train to include RO, and therefore produce high quality water.
- Treatment trains can match the reuse applications. The key differentiators in the treatment trains are:
    - Some provide basic Class A treatment for BOD/TSS removal only.

  - Some provide phosphorus removal and add nitrification to remove ammonia. Nitrification alone does not open reuse opportunities; but with phosphorus removal, additional reuse opportunities exist.
  - Some provide full nutrient removal.
  - Some provide advanced treatment to remove organics, metals, and TDS.
- The treatment processes evaluated in the pilot study can meet the basic objectives for rapid startup, small footprint, and remote operation.
- Treatment trains can be designed with enough flexibility to accommodate the addition of advanced treatment to meet the demands of a growing reuse market or to meet requirements for new reuse opportunities.

Table 14. Treatment Train Processes, Features, and Applications.

Component Processes												Effluent Quality					Potential Reuse Applications											
Train	BF	BAF1	BAF2	SBF	MBR	BF2	FF	Conv Filter	MF	RO	Disinfect	Low Turbidity	NH4 removal	TN removal	P removal	TDS/TOC removal	Class A	Wetland	GW Percolate	GW - Non Potable	GW Potable	Large Stream Marine	Small Stream Marine	Large Stream Lake	Small Stream Lake	Ballard Locks	Lake Expect	Lake Worst Case
B1	✓	✓						✓			✓					·	✓			3								
B2	✓	✓							✓		✓	✓			✓	·	✓			3								
B3	✓	✓	✓				✓				✓		✓			·	✓			✓[1]		✓				✓		
B3E	✓[2]	✓	✓				✓[2]				✓		✓		✓	·	✓			✓[1]		✓	✓			✓		
B4	✓	✓	✓			✓	✓				✓		✓		✓	·	✓			✓[1]		✓	✓	✓	✓	✓		
B5	✓	✓	✓						✓		✓	✓	✓		✓	·	✓			✓[1]		✓	✓			✓		
B5E	✓[2]	✓	✓						✓[2]		✓	✓	✓		✓	·	✓			✓[1]		✓	✓	✓	✓	✓		
B6	✓	✓	✓	✓			✓				✓		✓	✓		·	✓	✓	✓	✓[1]		✓	✓			✓		
B7	✓	✓	✓	✓		✓	✓				✓		✓	✓	✓	·	✓	✓	✓	✓[1]		✓	✓	✓	✓	✓		
B8	✓	✓	✓	✓					✓		✓	✓	✓	✓	✓	·	✓	✓	✓	✓[1]	✓[1]	✓	✓	✓	✓	✓		
B9	✓	✓							✓	✓	✓	✓			✓	✓	✓		✓	✓	✓	✓		✓				
B10	✓	✓	✓						✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
B11	✓	✓	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
M1					✓						✓	✓	✓			·	✓			3		✓				✓		
M1E					✓[2]						✓	✓	✓		✓	·	✓			3		✓	✓	✓	✓	✓		
M2					✓						✓	✓	✓	✓	✓	·	✓		✓	✓	✓	✓	✓	✓	✓	✓		
M3					✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
M3E					✓[2]					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
M4					✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes:
1. Application may require TDS removal
2. Chemical addition points for enhanced phosphorus removal
3. Nitrogen removal may be required

Abbreviations: BF – Ballasted Flocculation; BAF1 – Biological Aerated Filter for BOD removal; BAF2 – Biological Aerated Filter, second stage for nitrification; SBF – Submerged Biological Filter; MBR - Membrane Bioreactor; BF2 – Ballasted Flocculation for secondary phosphorus removal; FF – Fuzzy Filter; MF – Microfiltration; RO – Reverse Osmosis. NH4 – Ammonia; TN – Total nitrogen; P – Phosphorus; TDS – Total Dissolved Solids; TOC – Total Organic Carbon; GW – Groundwater